Simulating a Sequential Coalition Formation Process for the Climate Change Problem: First Come, but Second Served?

by

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Abstract

We analyze stability of self-enforcing climate agreements, considering a sequential coalition formation process of heterogeneous and farsighted players. Players can make proposals which are either accepted or countered by alternative proposals. We discuss the conceptual difficulties of implementing and solving such a game and the strategic options arising in a sequential process. This is illustrated with simple examples and with numerical simulations using the CLIMNEG world simulation model (CWSM).

Keywords: International Climate Agreements, Sequential Coalition Formation, Integrated Assessment Model

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1. Introduction

Cooperation in transboundary pollution has proven, and still proves, difficult. Despite the fact that cooperation among nations could raise global welfare because of multilateral negative externalities, and could benefit all nations if accompanied by fair sharing arrangements, strong free-rider incentives prevail. Curbing greenhouse gases illustrates the problems of cooperation vividly. International response to global warming is often traced back to 1988 when the Intergovernmental Panel on Climate Change (IPCC) was founded – an international body initiated by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) that gathers and summarizes current world-wide scientific evidence on climate change. However, it was not until 1997 when 38 countries agreed to emission ceilings under the Kyoto Protocol to be met in the "commitment period" 2008-2012. Again, it was not before 2002 when this treaty was ratified. This did not happen before several concessions had been granted to various participants and after the USA had declared to withdraw from the treaty.

Currently, in the light of the Stern report (Stern 2006) and the most recent IPCC report (IPCC 2007), a follow-up "Post-Kyoto" agreement is being negotiated that should set emission ceilings for the period after 2012. The challenge is to agree on substantial medium and long term emissions reduction targets for industrialized countries, and to encourage participation of the new emerging polluters China, India and Brazil.

Parallel to this political development, the interest in economics to analyze the reasons and possible remedies for the problem of international environmental cooperation emerged. One strand of literature focused on the game theoretic analysis of international environmental agreements (IEAs) which can be traced back to Barrett (1994), Chander and Tulkens (1992), Carraro and Siniscalco (1993) and Hoel (1992). Later papers focused on various designs and measures that could mitigate the free-rider problem. Due to the many papers, we refer the reader to the surveys by Barrett (2003) and Finus (2003, 2008). Other contributions departed from the assumption of a static payoff structure of the initial papers and captured the dynamic nature of the stock pollutants "greenhouse gases". This is also the starting point of the second strand of literature that modeled optimal policy responses in integrated assessment models that capture the dynamic interaction between the economy and the environment and which was pioneered by Nordhaus (1994). This initiated many other papers which are surveyed for instance in Böhringer and Löschel (2006). Naturally, there have also been attempts to combine both strands as for instance in Bahn et al. (2009), Bosello et al. (2003), Eyckmans and Tulkens (2003), Eyckmans and Finus (2006) and Weikard et al. (2006). On the one hand, this adds more realism to the analysis; on the other hand, this is sometimes the only way to derive results in richer game theoretic frameworks where analytical solutions are impossible to obtain.

This paper is in the tradition of a combined approach: it links a game theoretic module of coalition formation to an integrated assessment numerical simulation module. The later module is based on the CLIMNEG World Simulation Model (CWSM) as for instance used in Eyckmans and Tulkens (2003) and Eyckmans and Finus (2006), though we use the updated version 1.2. Different from these papers, but also different from many theoretical contributions on the formation and stability of IEAs, our game theoretic module does not model coalition formation as a simultaneous but as a sequential decision process. This is motivated by the observation that usually some countries take the initiative of forming IEAs. Others join later or decide not to follow suit. The evolvement of membership in international agreements is a typical feature of many IEAs and is reported for instance in Finus (2003) for many environmental treaties.

The sequential nature of the formation of international climate agreements introduces some new and interesting strategic aspects, but also poses many conceptual problems. This papers is a first step to address these problems, hoping to initiate more work in this important area of research.

We view coalition formation as a two-stage game. In the first stage players decide upon membership and in the second stage they decide upon their economic strategies, which are abatement strategies and in our simulation model also investment in capital and labor. The game is solved backward: equilibrium economic strategies determine the payoff of players and are the basis to decide upon membership. The second stage strategies are derived from a difference game among heterogeneous players, capturing the stock pollutant nature of greenhouse gases. For the membership decision in the first stage we consider a sequential process, though decisions are based on discounted payoffs. Thus, once coalitions have formed, membership is fixed. This contrasts to flexible membership considered in Breton et al. (2008), De Zeeuw (2007), Rubio and Ulph (2007) and Ulph (2004), invoking the concept of internal and external stability. However, all these papers assume symmetric players and allow only for a single coalition to be formed, probably for analytical tractability. Moreover, a simultaneous coalition formation process at each time t is assumed. This comparison already suggests an avenue for future research, namely the integration of both approaches in order to comprehensively capture the dynamic nature of the formation of agreements and the economic and environmental impacts of climate change.

In the following, we provide an overview of the model in section 2. Then we discuss stage 1 and 2 of coalition formation in reverse order (according to backward induction) in sections 3 and 4. The focus is on the novel aspect of this paper: the sequential membership process related to the first stage (section 4) with its strategic implications as well as the conceptual difficulties of implementing and solving such a game. This will be illustrated with two simple examples as a preparation for the more involved numerical simulations with our climate model CWSM which we present in section 5. Section 6 summarizes our results and concludes.

2. Overview of the Model

Following Bloch (2003), we view the coalition formation process as a two-stage game. In the first stage, players, $i \in I = \{1,...,n\}$, which are world regions in our numerical model, decide upon their membership in coalitions, which are climate agreements in our context. This stage is modeled along the lines of the sequential move unanimity game (SMUG) proposed by Bloch (1995). In this game, an initiator proposes a coalition. Prospective members of this coalition are sequentially asked for acceptance. If all potential members accept, the coalition is formed. If the proposed coalition is not the grand coalition, a new initiator among the remaining players can make a new proposal. If a player rejects a proposal, he can make a new proposal. The formation process continues until all players have agreed to be either a member of a (non-trivial) coalition or decided to remain a singleton.[1] The decision process in the first stage leads to some coalition structure $c = \{c_1,...,c_m\}$ where $c \in C$ is a partition of players in disjoint non-empty sets, $c_k \cap c_\ell = \emptyset \; \forall \; k \neq \ell$ and $\bigcup_\ell c_\ell = I$.

In the second stage, players choose their economic strategies, which are abatement and investment strategies in the CLIMNEG world simulation model (CWSM), based on the economic implications as estimated by this model. For a given coalition structure c, this implies a payoff vector $v(c) = (v_1(c),....,v_n(c))$. That is, a coalition structure $c \in C$ is mapped into a vector of individual payoffs $v(c) \in V(C)$ called valuations. In case a transfer scheme is implemented, this leads to "modified valuations" $v_i^T(c) = v_i(c) + \Psi_i$ where $\Psi_i > 0$ implies to receive a transfer and $\Psi_i < 0$ to pay a transfer with the understanding that transfers are only paid among coalition members and that transfers balance, i.e. $\sum_{i \in c_\ell} \Psi_i = 0 \;\; \forall \; c_\ell \in c$.

For the first stage, which consists of many sub-stages due to the sequential coalition formation process, we solve for the subgame-perfect equilibrium in membership strategies. That is, each player, either in the role of an initiator or in the role of a player who is asked for acceptance should choose her best reply at each point in time for the rest of the game, given the strategies of the other players.

1 A non-trivial coalition is a coalition with at least two members.

For the second stage, we follow the standard assumption in the literature on coalition formation and solve for the *coalitional Nash equilibrium* in economic strategies.[2] That is, members of coalition c_ℓ in coalition structure c choose their economic strategies such as to maximize the aggregate payoff to their coalition, taking the strategies of outsiders as given. In CWSM this payoff is the net present value of a payoff stream, accounting for the fact that climate change is a stock pollution problem.

We now discuss the stages in more detail in reverse order, following the argument of backward induction.

3. Second Stage of Coalition Formation

3.1 Data and Computations

The CWSM is an integrated assessment (IA in the sequel), economy-climate model capturing the endogenous feedback of climate change damages on production and consumption. As the seminal RICE model by Nordhaus and Yang (1996), and in subsequent IA models like Bosello et al. (2003), Böhringer et al. (2007), Bahn et al. (2009) or Anthoff et al. (2009), CWSM is a dynamic, long-term, perfect foresight, Ramsey-type optimal growth model with a global climate externality. The version of the CWS model used in this paper is an updated version of the model used in Eyckmans and Tulkens (2003). The new version of the CWS model uses the more sophisticated carbon cycle model of RICE99 described in Nordhaus and Boyer (2000). In addition to a better representation of the climate system, the economic database and parameters of the CWS model have been updated and the reference year is now 2000 instead of 1990. Since an extensive exposition of the model, including the procedure of computing valuations, is provided in Eyckmans and Tulkens (2003) and Eyckmans and Finus (2006 and 2009), we describe here only

2 For a summary of this literature in the general context, see Bloch (2003) and in the context of IEAs, see Finus (2003). Sometimes a coalitional Nash equilibrium is also called a coalitional equilibrium (Ichiishi 1981) or a partial Nash equilibrium between coalitions (Chander and Tulkens 1997).

its main features. A brief description of the main equations and parameters is provided in Appendix 1.

In CWSM, the world is divided into six regions: *USA*, *JPN* (Japan), *EU* (European Union), *CHN* (China), *FSU* (Former Soviet Union) and *ROW* (Rest of the World). The two basic choice variables, capital investment and emission abatement, affect output, abatement costs, damage costs and therefore also consumption domestically but also abroad. Finally, welfare is measured as total lifetime discounted consumption.

An economic strategy vector is denoted by $s^*(c)$ and consists in CWSM of a time path of 35 decades for emission abatement and investment for all six regions, hence its length is 2 x 35 x 6 = 420. Valuations without transfers $v(c)=(v_1(c),...,v_n(c))$ for coalition structure $c\in C$ are defined as $v_i(c):=W_i(s^*(c))$ where $s^*(c)$ is the coalitional Nash equilibrium economic strategy vector which is defined as:

$$(1) \qquad \forall c_\ell \in c: \sum\nolimits_{i\in c_\ell} W_i(s^*_{c_\ell}(c),s^*_{-c_\ell}(c)) \geq \sum\nolimits_{i\in c_\ell} W_i(s_{c_\ell}(c),s^*_{-c_\ell}(c)) \qquad \forall\, s_{c_\ell}(c)$$

where $W_i(\ )$ is the discounted payoff of player i, $s_{c_\ell}(c)$ is the economic strategy vector of coalition c_ℓ, $s_{-c_\ell}(c)$ the vector of all other regions not belonging to c_ℓ and an asterisk denotes equilibrium strategies. Determining $s^*(c)$ for every coalition structure $c\in C$ (noting $v_i(c):=W_i(s^*(c))$), gives the set of valuations $V(C)$.

Computationally, the coalitional Nash equilibria are computed by means of a standard iterative algorithm assuming that all members of coalition $c_\ell \in c$ jointly maximize the aggregate payoff to their coalition $\sum\nolimits_{i\in c_\ell} W_i(s)$ with respect to $s_{c_\ell}(c)$, while taking the strategies of outsiders $s_{-c_\ell}(c)$ as given. Repeating this optimization problem for each strategic player (coalition or singleton) and iterating until strategy vectors do not change more than some prespecified tolerance level, gives $s^{*}(c)$ which is substituted into W_i in order to derive $v(c)=(v_1(c),...,v_n(c))$.

Strategically, this means that members who belong to the same coalition behave cooperatively towards their fellow members (otherwise cooperation would not be worthwhile analyzing), but non-cooperatively towards outsiders. *Economically*, this means strategies are efficient within coalition c_ℓ but not globally efficient as long as the grand coalition does not form. It also means that the equilibrium economic strategy vector $s^{*}(c)$ corresponds to the classical "social or global optimum" if c is the coalition structure with the grand coalition, and corresponds to the classical "Nash equilibrium" if c is the coalition structure with only singletons.

Valuations with transfers are defined as $v_i^T(c)=v_i(c)+\Psi_i$ where the transfer Ψ_i is paid ($\Psi_i<0$) or received ($\Psi_i>0$) in a lump-sum fashion (expressed in discounted consumption at time $t=0$) and hence does not affect equilibrium economic strategies in the CWSM as shown in Eyckmans and Tulkens (2003). This implies a TU-framework and the transfer scheme proposed by these authors leads to valuations

$$(2) \qquad v_i^T(c)=v_i(c^N)+\lambda_i\left[\sum\nolimits_{j\in c_\ell}(v_j(c)-v_j(c^N))\right] \qquad \forall i\in c_\ell,\quad \forall c_\ell\in c.$$

That is, every region i in coalition $c_\ell \in c$ receives its payoff in the coalition structure with only singletons which is denoted by c^N (first term on the R.H.S. in (2); $c^N=\{\{1\},...,\{n\}\}$), and additionally a share $\lambda_i\geq 0$, $\sum\nolimits_{i\in c_\ell}\lambda_i=1$, from the total coalitional surplus of cooperation when moving from coalition structure c^N with no cooperation to some other coalition structure c (term in square brackets on the R.H.S. in (2)). Shares are those proposed by Eyckmans and Tulkens (2003) and reflect the relation between individual and global discounted marginal climate change damages in coalition structure c. Hence, the second term favors regions with relatively high marginal damages since they are entitled to a larger share of the surplus of their coalition.

3.2 Properties of Valuations

Table 1 displays individual valuations, generated by CWSM, with and without transfers for a selection of coalition structures.[3] The last two columns display aggregate valuations at the World level in absolute and relative terms. The relative magnitudes can be interpreted as a "closing the gap index" (abbreviated CGX), measuring how close a coalition structure comes to the global optimum where the performance in the grand coalition (full cooperation) is 100 percent and the performance in the coalition structure with only singletons (no cooperation) is 0 percent by definition (see the legend of Table 1).

Table 1 about here

Apart from stressing that both full and partial cooperation make a difference compared to no cooperation, Table 1 illustrates that not only the size of a coalition matters for the global success of cooperation, but also the identity of its members. Put differently, the commonly held view that a high participation automatically indicates the success of an IEA may be wrong. For instance, coalition structure No. 152 including the five members USA, JPN, EU, CHN and FSU ranks lower than many coalition structures comprising smaller coalitions as for instance coalition structure No. 150 and No. 151.

As a general tendency, the importance of particular regions for global welfare decreases along the following sequence: ROW, CHN, USA, EU, FSU and JPN. ROW´s and CHN´s important role stems from the fact that they can provide cheap abatement. Similarly, JPN´s lesser importance is due to her steep marginal abatement cost curve. However, there is also an additional dimension related to environmental damages. Because optimal economic strategies are derived from coalitions maximizing the joint welfare of its members, the higher the marginal damages of coalition members are, the higher joint abatement efforts will be, everything else being equal.

[3] We do not display the ecological implications (i.e. total emissions and concentration) of different coalition structures in this paper. For version 1 of CWSM, this is for instance provided in Eyckmans and Finus (2006). The complete matrix of valuations is available upon request from the authors.

This has not only a positive spillover effect on fellow coalition members but also on outsiders. This explains the importance of EU for cooperation.

4. First Stage of Coalition Formation

4.1 Original Game

Based on valuations, either on valuations with or without transfers, $V(C)$ or $V^T(C)$, derived in the second stage of coalition formation, players decide upon participation in coalitions in a sequential process. The process is modeled based on the sequential move unanimity game (SMUG) of Bloch (1995), though for our purposes some changes are necessary which we discuss below. This game is in the spirit of Rubinstein´s (1982) two-player alternating offers bargaining game and is a generalization of Chatterjee et al.´s (1993) extension to an n-player bargaining game. The SMUG assumes that players are ordered according to some rule. The player with the lowest index (initiator), say, player 1, starts by announcing a list of coalition members including himself. Every member on the list is asked whether he or she accepts the proposal. The player with the lowest index on this list is asked first, then the player with the second lowest index and so forth. If all players on the list agree, the coalition, say, c_1, is formed and coalitions among the remaining players $I \setminus c_1$ may form. The player with the lowest index among $I \setminus c_1$ becomes the new initiator. If a player rejects a proposal, he/she can make a new proposal.

Thus, a coalition only forms by unanimous agreement. Because a player can always reject a proposal, participation in a non-trivial coalition is voluntary. Both features are well in line with the institutional setting of international environmental agreements. It is also evident that players whose proposals have been turned down are still part of the formation process. They may become members of other coalitions than those they have proposed. Also players that have turned down a proposal are still part of the game since they can propose a new coalition. Only if n-1 players have already formed a coalition, the last remaining player will have no other choice than to remain a singleton. When the negotiation process terminates, all players receive their payoffs.

For simplification, Bloch (1995, 1996) assumes no discounting of valuations during this process. He also assumes that players who cannot agree on a coalition receive a payoff which is Pareto-dominated by payoffs in every coalition structure. Thus, the solution to the game becomes "finite". Moreover, he only considers stationary perfect equilibrium strategies in order to reduce the amount of possible equilibria. That is, strategies only depend on the current state (and not on the entire history of the game) in the negotiation process. A sequence of proposals is a perfect equilibrium if proposals and reactions to proposals are mutually best replies for each possible state in the remaining game.

To the best of our knowledge, until now, Bloch´s game has only be applied to economic problems with the assumption that all players have the same payoff function.[4] For ex-ante symmetric players, as this assumption has been termed in the literature, Bloch (1996) has shown that things simplify substantially since the identity of players does not matter and – in most economic examples of interest - payoffs to a player only depend on the sizes of his own and the remaining coalitions in a given coalition structure c.[5] Hence, the sequence in which players make proposals and counter-proposals, as well as the sequence according to which players are asked for acceptance does not matter for the outcome of coalition formation. Moreover, a proposal means to announce the size of a coalition to which the proposer wants to belong and hence the entire

4 See Bloch (2003) for an overview. Bloch's game has been applied for instance by Finus and Rundshagen (2006a) and Ray and Vohra (2001) in the context of the provision of public goods; both applications assuming symmetric players.

5 For instance, in a global emission abatement game with a static payoff function Finus and Rundshagen (2003) have shown that, in a given coalition structure, members of larger coalitions receive a lower valuation than members of smaller coalitions because all players receive the same benefits from global abatement but members of larger coalitions choose higher individual abatement levels and therefore have higher abatement costs.

game reduces to a "size announcement game" in which the interests of the proposer and the members of the proposed coalition always coincide.

4.2 Modified Game

As pointed out already, we consider heterogeneous players and therefore the sequence of proposals matters. Hence, we have to solve for the equilibrium coalition structure for every possible index sequence of which there are 720 in the case of six players. Section 5 will focus on the effect of different sequences on the outcome of coalition formation. Important questions will be for instance: which regions should be among the initiators in order to induce successful cooperation from a global point of view? Is it an advantage to be an initiator or is a wait-and-see-strategy more promising for individual regions?

Generally, the bargaining game may have no solution. Suppose players have completely contrary preferences about their most preferred outcome. Then if all players insist on their most preferred outcome, this may lead to an infinite number of proposals, rejections and counterproposals. As mentioned, Bloch avoids infinite cycles by assuming that if players do not agree in finite time, they will end up with a Pareto-inferior outcome compared to the valuations of all possible coalition structures. Though this may seem an elegant solution in a theoretical setting, we think it is less appropriate in our context. Viewing the coalition structure with only singletons as the starting point of negotiations, there seems to be no plausible reason why regions should not receive at least this payoff if negotiations fail. Therefore, we follow a pragmatic approach that is inspired by software programs used for chess computers. At the time of an ongoing proposal and as long as no additional coalition has formed, the same player cannot make a second proposal if his/her first proposal has been turned down. It is important to note that this rule only applies if the game does not proceed. If a coalition has eventually formed at stage t, this player can again make a proposal at $t+1$ (provided he/she has not accepted already another proposal).

We call Bloch's slightly modified coalition game SMUG Finite Sequential Move Unanimity Game (FSMUG). We order players, i.e. regions in CWSM, randomly and then generate all permutations. Since like in Bloch (1995), the relevant history at time t depends only on the current state of the game at time t (and not on the entire history of the game, equilibrium coalition structures are derived as stationary perfect equilibrium. A backtracking algorithm along the lines for instance described in Alho et al. (1987) was programmed in Java, version 1.4.2 in order to determine these equilibria in the FSMUG for the valuations computed with the numerical CWS model.

4.3 Properties and Strategies

We first briefly and informally show that our FSMUG - applied to our valuations $V(C)$ and $V^T(C)$ derived from CWSM - possesses some essential properties which are important for determining equilibrium coalition structures. Then, we illustrate some interesting implications for the optimal strategies of players. For this we use simple examples with three players as the driving forces would be difficult to trace in our application with six players.

First note that an equilibrium in the FSMUG always exists and the equilibrium coalition structure is unique for a given index sequence. This follows from three items: a) the game tree is finite by construction, b) there is perfect information with respect to the history of the game and hence every information set consists of only one decision node and c) at every decision node every player has a strict preference order over all coalition structures for the valuations generated by CWSM.

Second note that all equilibria (e.g. emerging from different index sequences or different sets of valuations) will be individually rational, meaning that every player receives a payoff in excess of the payoff in the coalition structure with only singletons. Regardless of the coalition which has formed in the game, a player i can always remain a singleton by proposing coalition $\{i\}$. This strategy ensures him at least the payoff in the singleton coalition structures because the CWSM valuation functions satisfy the so-called positive externality property. This property says that outsiders to a coalition cannot lose from the merger of other players and/or coalitions (e.g. Bloch (2003), Yi (2003) and Finus and Rundshagen 2006b).

Example 1 in Table 2 shall illustrate the interesting phenomenon that a player may intentionally put forward a proposal that she knows will be turned down. First note that players 2 and 3 derive their highest valuation when the other two players form a coalition and they free-ride. Hence, if either player 2 or 3 is the initiator, they propose a single coalition. Since the singleton coalition structure c^1 is Pareto-dominated by all other coalition structures, the remaining players will form a coalition of two players. Thus, if player 2 is the initiator $c^3 = \{\{1,3\},\{2\}\}$ and if player 3 is the initiator, $c^2 = \{\{1,2\},\{3\}\}$ will emerge as the equilibrium coalition structure.

Example 1: Provoked Non-Acceptance Game

Coalition Structure	$v_1(c)$	$v_2(c)$	$v_3(c)$	$\sum_{i=1}^{3} v_i(c)$
$c^1 = \{\{1\},\{2\},\{3\}\}$	0	0	0	0
$c^2 = \{\{1,2\},\{3\}\}$	2	2	8	12
$c^3 = \{\{1,3\},\{2\}\}$	8	8	2	18
$c^4 = \{\{1\},\{2,3\}\}$	4	4	4	12
$c^5 = \{\{1,2,3\}\}$	7	7	7	21

A more interesting strategy is observed when player 1 is the initiator. Her most preferred coalition structure is $c^3 = \{\{1,3\},\{2\}\}$. However, suppose she proposed this, then player 3 would turn down her offer and would simply propose $\{3\}$. Now, player 1 and 2 would have no better option than to agree on forming a coalition together and hence $c^2 = \{\{1,2\},\{3\}\}$ would form which is player 1's second worst option. Thus, player 1 proposes $\{1,2\}$ which she knows will not be accepted by player 2. That is, she passes on the right to make a proposal to player 2, knowing that he will act in her best interest: player 2 will propose $\{2\}$ so that player 3 has to give in and forms a coalition with player 1. Hence, $c^3 = \{\{1,3\},\{2\}\}$ emerges as the equilibrium.

In other words, players 1 and 2's interest are in line and player 1 can only get her way be letting player 2 make the first effective move. Hence, $c^3 = \{\{1,3\},\{2\}\}$ is the equilibrium if player 1 is the initiator.

Example 1 also illustrates that the equilibrium outcome depends on the sequence of players. Moreover, moving first can be associated with an advantage. Regardless who kicks off the game, he/she can implement his/her most preferred coalition structure. That this is not always true will be illustrated in example 2 below.

In example 2 there are only two Pareto-undominated coalition structures, namely c^2 and c^5. Coalition structure c^2 is the most preferred outcome of player 1 and c^5 of players 2 and 3. Suppose player 1 is the initiator. If she proposed $\{1,2\}$, and player 2 accepted, then c^2 would form. However because c^2 is only player 2's second best option, and player 2 and 3 both prefer the grand coalition c^5, player 2 could propose the grand coalition. Given that player 1 cannot make a new proposal as long as the game has not proceeded, and the grand coalition Pareto-dominates the singleton coalition structure c^1, player 1 would accept this proposal. However, c^5 is only player 1's third-best alternative. Consequently, player 1, anticipating all this, proposes $\{1\}$ in equilibrium, knowing that players 2 and 3 prefer to form a coalition together instead of remaining singletons. Thus, the equilibrium coalition structure if player 1 is the initiator (regardless how players 2 and 3 are ordered), is coalition structure $c^4 = \{\{1\},\{2,3\}\}$.

Example 2: Pareto-dominated Equilibrium Game

Coalition Structure	$v_1(c)$	$v_2(c)$	$v_3(c)$	$\sum_{i=1}^{3} v_i(c)$
$c^1 = \{\{1\},\{2\},\{3\}\}$	0	0	0	0
$c^2 = \{\{1,2\},\{3\}\}$	6	2	4	12
$c^3 = \{\{1,3\},\{2\}\}$	1	1	1	3
$c^4 = \{\{1\},\{2,3\}\}$	5	1	3	9
$c^5 = \{\{1,2,3\}\}$	3	6	5	14

Since c^4 is Pareto-dominated by c^2, this example illustrates that there are instances where a Pareto-dominated equilibrium coalition structure can emerge as an equilibrium due to strategic considerations. Moreover, it shows that an initiator cannot always push through his/her most preferred outcome. This is also the case if either player 2 or 3 are the initiators, though in this case the Pareto undominated coalition structure c^2 is the equilibrium outcome.

If either player 2 or 3 moves first, he/she anticipates that he/she cannot enforce his/her most preferred coalition structure c^5 as player 1 will raise objections. Hence, both players try to enforce their second-best option which is c^2 and which they know will be accepted by player 1, as it is her first-best option. Hence, if player 2 is the initiator, he will propose $\{1,2\}$, which player 1 will accept, leaving player 3 as a singleton. If player 3 is the initiator, she proposes $\{3\}$ and player 1 and 2 form $\{1,2\}$.

Thus, if either player 2 or 3 is the initiator, they cannot implement their first choice as an equilibrium (as this is the case if player 1 is the initiator). Even more important, they make proposals which lead to the most preferred coalition structure of player 1. In other words, from player 1's point of view, there is an advantage not to move first.

5. Results

5.1 Base Case

In this section we display and discuss equilibrium coalition structures based on the valuations in CWSM. Table 2 displays equilibrium coalition structures for the case of no transfers and the case of transfers. In the case of no transfers, there are 11 equilibrium coalition structures, in the case of transfers, there are only two. Equilibrium coalition structures are sorted according to welfare at the world level in descending order. The ranks for different regions within the set of equilibria are indicated in the columns under the heading "Ranking". The first entry in the column "PO" indicates whether the coalition structure is Pareto-undominated among the entire set of coalition structures of which there are 203. The second entry in this column indicates whether the coalition structure is Pareto-undominated among the set of equilibrium coalition structures. The frequency of occurrence of a coalition structure among the 720 possible index sequences is indicated in the last column.

Table 2 about here

We would like to point out four general observations. First, equilibrium coalition structures emerge that are not a PO among the set of possible coalition structures. This possibility was illustrated in example 2 in section 4.4 and is due to the strategic characteristics of a sequential coalition formation process. As in example 2, this even occurs if Pareto-dominance is only checked among the set of equilibrium coalition structures.

Second, nearly all equilibrium coalition structures include multiple non-trivial coalitions. Hence, if players have a wider choice of options than only joining an agreement or remaining a singleton, coalition structures with multiple coalitions emerge in equilibrium. This observation is in line with simulation results for instance in Finus et al. (2009) and Eyckmans and Finus (2006) and the theoretical findings in Carraro (2000) and Finus and Rundshagen (2003), though they assume a simultaneous coalition formation process under various membership rules. The relative high average CGX is due to the fact that the FSMUG de facto implies that a coalition only forms if and only if all players unanimously agree to form exactly this coalition. That is, a high degree of unanimity is conducive to the success of coalition formation as spelled out for instance in Eyckmans and Finus (2006) and Finus and Rundshagen (2006b). However, the grand coalition is not stable.

Third, transfers lead to a higher average CGX than no transfers. Transfers seem to align interests more among heterogeneous players for our data set, as they lead to a more symmetric distribution of the gains from cooperation (at least all coalition structures are individually rational), which leads to one equilibrium coalition structure in 98 percent of the possible index sequences. This is different for no transfers where the index sequence matters much more. Nevertheless, also here the first three ranked equilibrium coalition structures (which are Pareto-undominated) appear with a frequency of 599 all together, amounting to 83 percent of the possible index sequences. All together, we confirm the positive effect of transfers for the success of coalition formation that has been found for simultaneous coalition formation games. See for instance Botteon and Carraro (1997), Carraro et al. (2006), Eyckmans and Finus (2006), Weikart et al. (2006) among many others.

Fourth, irrespective whether we consider no transfers or transfers, there is no equilibrium coalition structure which is the most preferred for a particular region among the entire set of coalition structures.[6] In other words, no region, regardless of the sequence in which they make proposals, can enforce its most preferred coalition structure. A similar conclusion, though less pronounced emerges from Table 3.

Table 3 looks at the most preferred and least preferred equilibrium from a region's point of view among the set of equilibrium coalition structures. Percentages indicate the frequency that region i is among the first three in the index sequence when this equilibrium emerges. For instance,

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[6] This is evident by comparing Table 1 and 2.

USA's most preferred equilibrium for no transfers is the first equilibrium coalition structure displayed in Table 2. It occurs 32 times. In 30 instances, the USA is among the first three players and hence 30/32=93.8%. Thus, the USA has a first mover advantage when it comes to her most preferred equilibrium. Similarly, USA's worst equilibrium is ranked no. 10 at the world scale (see Table 2, no transfers). It occurs 78 times and in 12 instances the USA is among the first three players and hence 12/78=15.4%. Put differently, in 84.6% of the cases the USA cannot avoid the worst outcome because of her late mover position. This relation can be interpreted as a first mover advantage to avoid bad outcomes.

The other entries for other regions in Table 3 are computed in the same way. Hence, in row "Best Equilibrium", a percentage above 50% indicates a first mover advantage (indicated bold) and in row "Worst Equilibrium" this is true for a percentage below 50% (indicated bold). Thus, only in the case of transfers there seems to be on average a first mover advantage. This is in line with our example 2 in section 4.4 which showed that it is not always in the interest of a player to move first, i.e. there may be a last or later mover advantage. It appears that – on average - there is a first-mover advantage to avoid the worst outcome.

In the context of the provision of a public good, two incentives can roughly be identified to explain this, though incentives are far more complex for the valuations derived from CWSM. On the one hand, moving first provides the possibility to free-ride by either proposing to remain a singleton or being only a member of a small coalition. This, however, requires that the player can expect that others cooperate if he commits to little cooperation. On the other hand, it can also be advantageous to move later in the game, hoping that others commit to cooperation. In a simple symmetric player context and public good provision Finus and Rundshagen (2006a) have shown that only the first incentive is at work.[7] Now, in the case of heterogeneous players, obviously, also the second incentive seems to be relevant in some instances.

5.2 Sensitivity Analysis

Since our results have been obtained by simulations, we test the robustness of our conclusions. As appears from the discussion in the previous sections, we are not interested in quantitative results, but in qualitative conclusions. This seems suggestive given the large uncertainty surrounding the calibration of the parameters of integrated assessment models. Among the main parameters that enter CWSM, we focus on a variation of the discount rate as there has been much debate about the appropriate choice of the discount rate (time preference rate). Hence, we consider instead of $\delta = 0.01$ (see Appendix 1) also two other values, $\delta = 0.02$ and $\delta = 0.03$, for which we produce tables in the spirit of Tables 2 and 3 and which are available upon request. From this sensitivity analysis the following conclusions can be drawn.

Despite the fact that the composition of some equilibrium coalition structures is different, all conclusions turn out to be very robust. Average success rates measured as average CGX remain very similar. The general observations mentioned in section 5.1 also remain true. Equilibrium coalition structures emerge that are not Pareto-optimal among the entire set of coalition structures and some are even Pareto-dominated by other equilibrium coalition structures, and this happens more frequently in the absence of transfers.

Nearly all equilibrium coalition structures comprise multiple non-trivial coalitions and transfers usually lead to a higher average CGX. Regions can never push through their most preferred coalition structure regardless of the sequence in the negotiations, though there is now one exception: FSU. However, interestingly, when this most preferred coalition structure emerges, the percentage of instances in which FSU is among the first three regions in the index sequence is

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[7] In example 1 in section 4.4, this free-rider incentive could also be observed if either player 2 or 3 moves first, though the game is not symmetric.

below 50%, suggesting that there is no first but a later mover advantage for FSU. Also for other players there is no indication of first-mover advantage on average concerning their most preferred outcome, suggesting that a wait-and-see-strategy can be attractive to the participants in climate negotiations.

6. Summary and Conclusions

We combined two modules, an empirical model on climate change and a game theoretic model of coalition formation, to study self-enforcing climate agreements. The empirical model was the Climate Change World Simulation Model (CWSM), version 1.2, which is a dynamic optimal growth model that captures the feedback between the economy and climate change for six world regions. We computed payoffs for all possible partitions of players, called valuations, allowing for the possibility of the co-existence of several coalitions. Based on these valuations, we determined stable coalition structures.

We considered a new conceptual issue of coalition formation in the context of IEAs: a sequential coalition formation process. This was motivated by the empirical evidence that participation in IEAs has evolved sequentially in the past. We argued that the sequential move unanimity game proposed by Bloch (1995) has to be modified for practical purposes in order to avoid infinite cyclical proposals. We introduced the assumption that a player whose proposal has been turned down, cannot make a second proposal as long as the formation process has not proceeded. This allowed us to develop a backtracking algorithm to solve for equilibrium coalition structures.

One part of our results illustrated the strategic properties of a sequential coalition formation process. For instance, we showed that there is not always a first-mover advantage, but a wait-and-see-strategy may well pay. Negotiators may even have an incentive to put forward a proposal which they know will be turned down in order to benefit from a later mover advantage. Due to strategic considerations and strong free-rider incentives, equilibrium coalition structures may not be Pareto-optimal. It also clearly emerged that it is very unlikely that single negotiators can push through their most preferred outcome, irrespective of the sequence when they move.

Another part of the results confirmed conclusions derived from a simultaneous coalition formation process. Due to large asymmetries across the world in the climate change context in terms of the environmental damages and abatement cost, compensation payments are conducive to establish effective cooperation. Moreover, if participation is not restricted exogenously to a single agreement, multiple coalitions will emerge as equilibrium outcomes. As argued for instance in Eyckmans and Finus (2006) and Finus et al. (2009), this may be taken as indication to revise previous policy strategies. As long as free-rider incentives do not allow forming a climate agreement with full participation, it may be worthwhile to allow for bilateral agreements instead of focusing on a single treaty.

From our results important avenues for future research emerge. In particular, we believe that more conceptual work is needed to comprehensively capture the dynamic nature of the formation of IEAs in terms of the sequence of proposals, participation, policy goals, enforcement and the stock pollutant nature of greenhouse gases. This is certainly a non-trivial challenge but would help to base policy recommendations for the design of successful future IEAs on a more realistic basis. After all, it is not to be expected that problems like climate change, the depletion of the ozone layer or biodiversity will disappear in the future.

References

Alho, A.V., J.E. Hopcroft, J.D. Ullman (1987), Data Structures and Algorithms. Addision-Wesley, Reading (Mass.).

Anthoff, E., C. Hepburnd and R.S.J. Tol (2009), Equity Weighting and the Marginal Damage Costs of Climate Change. Ecological Economics, vol. 68, pp. 836-849.

Bahn, O., M. Breton, L. Sbragia and G. Zaccour (2009), Stability of International Environmental Agreements: an Illustration with Asymmetrical Countries. International Transactions in Operational Research, vol. 16, pp. 307-324.

Barrett, S. (1994), Self-enforcing International Environmental Agreements. Oxford Economic Papers, vol. 46, pp. 878-894.

Barrett, S. (2003), Environment and Statecraft: The Strategy of Environmental Treaty-making. Oxford University Press, New York.

Bloch, F. (1995), Endogenous Structures of Association in Oligopolies. RAND Journal of Economics, vol. 26(3), pp. 537-556.

Bloch, F. (1996), Sequential Formation of Coalitions in Games with Externalities and Fixed Payoff Division. Games and Economic Behavior, vol. 14(1), pp. 90-123.

Bloch, F. (2003), Non-cooperative Models of Coalition Formation in Games with Spillovers. In: Carraro, C. (ed.), The Endogenous Formation of Economic Coalitions. Edward Elgar, Cheltenham, UK et al., ch. 2, pp. 35-79.

Bosello, F., B. Buchner and C. Carraro (2003), Equity, Development, and Climate Change Control. Journal of the European Economic Association, vol. 1(2-3), pp. 601-611.

Böhringer, C. and A. Löschel (2006), Computable General Equilibrium Models for Sustainability Impact Assessment : Status Quo and Prospects. Ecological Economics, vol. 60, pp. 49-64.

Böhringer, C., A. Löschel and T.F. Rutherford (2007), Decomposing the integrated assessment of climate change, Journal of Economic Dynamics & Control, vol. 31, pp. 683-702.

Botteon, M. and C. Carraro (1997), Burden-Sharing and Coalition Stability in Environmental Negotiations with Asymmetric Countries. In: Carraro, C. (ed.), International Environmental Negotiations: Strategic Policy Issues. Edward Elgar, Cheltenham, UK et al., ch. 3, pp. 26-55.

Breton, M. Sbragia, L. and Zaccour, G. (2008), A Dynamic Model for International Environmental Agreements. FEEM Working Papers 33.2008, forthcoming in Environmental and Resource Economics.

Carraro, C. (2000), Roads towards International Environmental Agreements. In: Siebert, H. (ed.), The Economics of International Environmental Problems. Mohr Siebeck, Tübingen, pp. 169-202.

Carraro, C., J. Eyckmans and M. Finus (2006), Optimal Transfers and Participation Decisions in International Environmental Agreements. Review of International Organizations, vol. 1, pp. 379-396.

Carraro, C. and D. Siniscalco (1993), Strategies for the International Protection of the Environment. Journal of Public Economics, vol. 52(3), pp. 309-328.

Chander, P. and H. Tulkens (1992), Theoretical Foundations of Negotiations and Cost Sharing in Transfrontier Pollution Problems. European Economic Review, vol. 36(2-3), pp. 388-399.

Chander, P. and H. Tulkens (1997), The Core of an Economy with Multilateral Environmental Externalities. International Journal of Game Theory, vol. 26(3), pp. 379-401.

Chatterjee, K., B. Dutta, D. Ray and K. Sengupta (1993), A Noncooperative Theory of Coalitional Bargaining. Review of Economic Studies, vol. 60(2), pp. 463-477.

Eyckmans, J. and M. Finus (2006), Coalition Formation in a Global Warming Game: How the Design of Protocols Affects the Success of Environmental Treaty-making. Natural Resource Modeling, vol. 19, pp. 323-358.

Eyckmans, J. and Finus, M. (2009), Transfer Schemes and Institutional Changes for Sustainable Global Climate Treaties. In: Guesnerie; R. and H. Tulkens (eds.), The Design of Climate Policy, MIT Press, Cambridge, MA, 2009, pp. 103-135.

Eyckmans, J. and H. Tulkens (2003), Simulating Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem. Resource and Energy Economics, vol. 25(4), pp. 299-327.

Finus, M. (2003), Stability and Design of International Environmental Agreements: The Case of Global and Transboundary Pollution. In: Folmer, H. and T. Tietenberg (eds.), International Yearbook of Environmental and Resource Economics 2003/4. Edward Elgar, Cheltenham, UK et al., ch. 3, pp. 82-158.

Finus, M. (2008), Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks and Future Challenges. International Review of Environmental and Resource Economics, vol. 2, pp. 1-39.

Finus, M. and B. Rundshagen (2003), Endogenous Coalition Formation in Global Pollution Control: A Partition Function Approach. In: Carraro, C. (ed.), The Endogenous Formation of Economic Coalitions. Edward Elgar, Cheltenham, UK et al., ch. 6, pp. 199-243.

Finus, M. and B. Rundshagen (2006a), Participation in International Environmental Agreements: The Role of Timing and Regulation. Natural Resource Modeling, vol. 19, 2006, pp. 165-200.

Finus, M. and B. Rundshagen (2006b), A Micro-Foundation of Core-Stability in Positive Externality Coalition Games. Journal of Institutional and Theoretical Economics, vol. 162, pp. 329-346.

Finus, M., M.E. Sáiz and E.M.T. Hendrix (2009), An Empirical Test of New Developments in Coalition Theory for the Design of International Environmental Agreements. Environment and Development Economics, vol. 14, pp. 117-137

Hoel, M. (1992), International Environment Conventions: The Case of Uniform Reductions of Emissions. Environmental and Resource Economics, vol. 2(2), pp. 141-159.

IPCC (2007), Climate Change 2007, Synthesis Report.

Ichiishi, T. (1981), A Social Coalitional Equilibrium Existence Lemma. Econometrica, vol. 49(2), pp. 369-377.

Nordhaus, W.D. (1994), Managing the Global Commons: The Economics of Climate Change. MIT Press, Cambridge, MA.

Nordhaus, W.D. and Z. Yang (1996), A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. American Economic Review, vol. 86(4), pp. 741-765.

Nordhaus, W.D. and J. Boyer (2000), Warming the World: Economic Models of Global Warming. MIT Press, Cambridge USA.

Ray, D. and R. Vohra (2001), Coalitional Power and Public Goods. Journal of Political Economy, vol. 109(6), pp. 1355-1384.

Rubinstein, A. (1982), Perfect Equilibrium in a Bargaining Model. Econometrica, vol. 50, pp. 97-109.

Rubio S. J., Ulph A. (2007), An Infinite-horizon Model of Dynamic Membership of International Environmental Agreements. Journal of Environmental Economics and Management, vol. 54, pp. 296-310.

Ulph, A. (2004), Stable International Environmental Agreements with a Stock Pollutant, Uncertainty and Learning. Journal of Risk and Uncertainty, vol. 29(1), pp. 53-73.

Stern, N. (2006), Stern Review: The Economics of Climate Change. Report prepared for the HM Treasury in the UK. Now published 2007: Cambridge University Press, Cambridge, UK.

Weikard, H.-P., M. Finus and J.-C. Altamirano-Cabrera (2006), The Impact of Surplus Sharing on the Stability of International Climate Coalitions. Oxford Economic Papers, vol. 58(2), pp. 209-232.

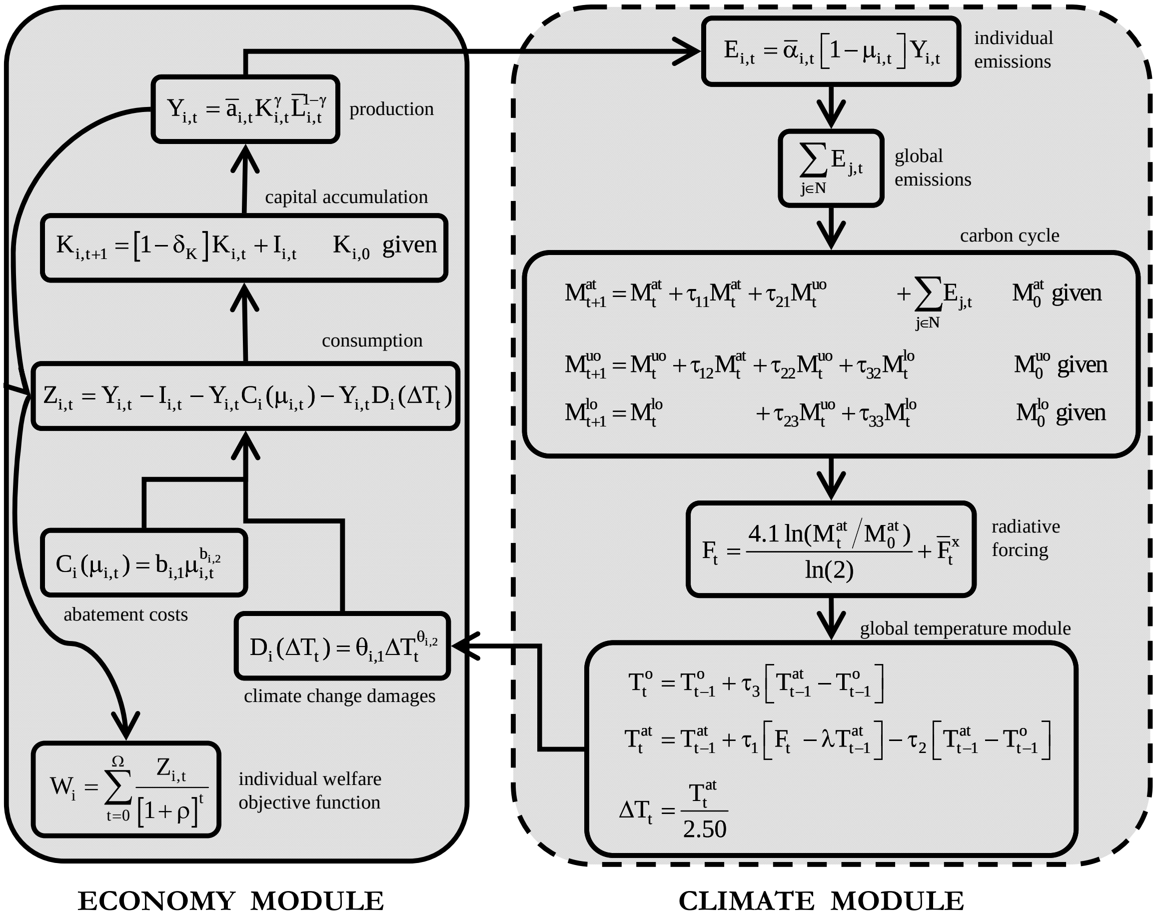
Yi, S.-S. (2003), Endogenous Formation of Economic Coalitions: a Survey of the Partition Function Approach. In: Carraro, C. (ed.), The Endogenous Formation of Economic Coalitions. Edward Elgar, Cheltenham, UK et al., ch. 3, pp. 80-127.

De Zeeuw, A. (2007), Dynamic Effects on the Stability of International Environmental Agreements. Journal of Environmental Economics and Management, vol. 55 (2), pp. 163-174.

Appendix 1

Figure A.1 shows the CLIMNEG World Simulation Model[8], version 1.2, which consists of two main blocks of equations: the economy (left) and the climate module (right). Subindices t denote time (in steps of 10 years[9]) and indices i indicate the region. Exogenous processes are indicated by an overbar.

Figure A.1: Schematic Overview of CLIMNEG World Simulation Model



[8] The GAMS code for the simulations is available from the authors upon request, including the entire matrix of valuations.

[9] In order to save space, the equations shown in Figure A.1 are simplified to an annual representation of the stock variables' accumulation processes. Using a time step different than one year, alters slightly the look of these equations but does not affect the essential aspects of the processes.

Table A.1: List of Variables and Functions

$Y_{i,t}$	production (billion US$_{2000}$)
$Z_{i,t}$	consumption (billion US$_{2000}$)
$I_{i,t}$	investment (billion US$_{2000}$)
$K_{i,t}$	capital stock (billion US$_{2000}$)
$E_{i,t}$	carbon emissions (billion tons of carbon, btC)
$\mu_{i,t}$	emission reduction (between zero and one)
$C\left(\mu_{i,t}\right)$	emission reduction cost function (fraction of GDP, between zero and one)
ΔT_t	global mean temperature change (°C)
$D_i\left(\Delta T_t\right)$	climate change damage function (fraction of GDP, between zero and one)
W_i	welfare measured as aggregated discounted consumption
M_t^{at}	atmospheric carbon concentration (btC)
M_t^{uo}	carbon concentration in upper strata ocean (btC)
M_t^{lo}	carbon concentration in lower strata ocean (btC)
F_t	radiative forcing (Watt per m^2)
T_t^{at}	atmospheric temperature (°C)
T_t^0	lower ocean temperature (°C)

Table A.2: Global Parameters

$\bar{a}_{i,t}$	Productivity	exogenous	
$\bar{L}_{i,t}$	Population	exogenous	
$\bar{\alpha}_{i,t}$	emission-output rate	exogenous	
$\bar{F}_t^x$	Exogenous radiative forcing	exogenous	
δ_K	annual rate of capital depreciation	0.10	
γ	capital productivity parameter	0.25	
ρ	annual rate of time preference	0.01*	
Ω	terminal year	2330	
τ_{11}	parameter carbon cycle	-0.033384	
τ_{12}	parameter carbon cycle	0.033384	
τ_{21}	parameter carbon cycle	0.027607	
τ_{22}	parameter carbon cycle	-0.039103	
τ_{23}	parameter carbon cycle	0.011496	
τ_{32}	parameter carbon cycle	0.000422	
τ_{33}	parameter carbon cycle	-0.000422	
τ_1	parameter global temperature module	0.226	
τ_2	parameter global temperature module	0.440	
τ_3	parameter global temperature module	0.020	
λ	parameter global temperature module	1.410	
M_0^{at}	Initial (=2000) atmospheric carbon concentration	783	btC
M_0^{uo}	Initial (=2000) carbon concentration in upper strata ocean	807	btC
M_0^{lo}	Initial (=2000) carbon concentration in lower strata ocean	19238	btC
T_0^{at}	Initial (=2000) atmospheric temperature	0.622	°C
T_0^{0}	Initial (=2000) lower ocean temperature	0.108	°C

* The sensitivity analysis is conducted for values 0.02 and 0.03.
Details for the time path of exogenous parameters and calibration of carbon cycle and temperature module are available from the authors upon request.

Table A.3: Regional Parameters

	$\theta_{i,1}$	$\theta_{i,2}$	$b_{i,1}$	$b_{i,2}$
USA	0.01102	2.0	0.07	2.887
JPN	0.01174	2.0	0.05	2.887
EU	0.01174	2.0	0.05	2.887
CHN	0.01523	2.0	0.15	2.887
FSU	0.00857	2.0	0.15	2.887
ROW	0.02093	2.0	0.10	2.887

Source: RICE_96 model by Nordhaus and Yang (1996).

Table A.4: Regional Initial (=2000) Data

	$Y_{i,0}$	$L_{i,0}$	$K_{i,0}$	$E_{i,0}$
USA	7563.810	282.224	19740.689	1.574
JPN	3387.931	126.87	9753.970	0.330
EU	8446.901	377.136	22804.477	0.888
CHN	968.906	1262.645	2686.056	0.947
FSU	558.436	287.893	1490.038	0.626
ROW	6633.427	3715.663	14105.209	2.192
WORLD	27559.411	6052.431	70580.438	6.556
	billion US$$_{2000}$ (market exchange rate)	million people	billion US$$_{2000}$	billion tons carbon btC (fossil fuel use)

Source: World Resources Institute http://www.wri.org (for $Y_{i,0}$ and $E_{i,0}$), UN Economic and Social Affairs division (for $L_{i,0}$) and own calibration (for $K_{i,0}$). Details are available from the authors upon request.

Table 1: Overview of Selected Coalition Structures and their Welfare Implications*

Rank	Coalition Structure	Valuations without Transfers						Valuation with Transfers							
		USA	JPN	EU	CHN	FSU	ROW	USA	JPN	EU	CHN	FSU	ROW	World	CGX
1	{USA,JPN,EU,CHN,FSU,ROW}	255882.2	48068.1	179478.3	308069.3	19038.2	**359617.9**	257401.2	48116.1	179507.6	307220.6	19417.5	**358490.8**	1170154	100.0
2	{USA,EU,CHN,FSU,ROW},{JPN}	255793.3	**48435.0**	179368.4	307762.0	19041.8	359127.1	257267.1	48435	179408.9	306960.3	19408.5	358047.7	1169528	97.9
3	{USA,JPN,EU,CHN,ROW},{FSU}	255686.8	48029.6	179319.5	307610.7	**19622.1**	358882.0	257232.0	48085.9	179385.9	306892.3	**19622.1**	357932.4	1169151	96.7
4	{USA,EU,CHN,ROW},{JPN,FSU}	255613.6	48393.4	179229.2	307361.9	19603.1	358486.6	257119.4	**48448.9**	179306.9	306685.0	19547.6	357580.0	1168688	95.1
5	{USA,EU,CHN,ROW},{JPN},{FSU}	255590.1	48390.2	179212.7	307314.3	19604.3	358409.0	257095.3	48390.2	179289.9	306638.8	19604.3	357502.2	1168521	94.6
6	{USA,JPN,CHN,FSU,ROW},{EU}	255592.8	47979.2	**180526.1**	307021.0	19059.2	357931.3	256915.2	48029.0	**180526.1**	306307.3	19386.1	356945.9	1168110	93.2
16	{USA},{JPN,EU,CHN,FSU,ROW}	**258283.8**	47886.3	178712.9	305884.7	19045.5	356069.0	**258283.8**	47963.2	178896.8	305609.3	19362.1	355767.0	1165882	85.8
17	{USA,JPN,EU,FSU,ROW},{CHN}	255393.4	47872.6	178657.4	**308478.0**	19117.0	356225.0	256298.4	47919.5	178721.3	**308478.0**	19345.0	354980.3	1165743	85.4
150	{USA},{JPN},{EU},{CHN}, {FSU,ROW}	255723.7	47788.2	178265.1	304393.3	19155.1	352360.0	255723.7	47788.2	178265.1	304393.3	19289.5	352225.5	1157685	58.6
151	{USA},{JPN,ROW},{EU},{CHN}, {FSU}	255705.1	47660.4	178251.7	304362.0	19332.1	352195.0	255705.1	47759.9	178251.7	304362.0	19332.1	352095.5	1157506	58.1
152	{USA,JPN,EU,CHN,FSU},{ROW}	253310.9	47467.0	176958.1	300739.6	19016.4	350146.7	253718.4	47470.1	176907.2	300219.1	19177.1	350146.7	1147639	25.3
157	{USA,JPN,CHN,FSU,},{EU}, {ROW}	253151.6	47416.4	177134.2	300178.2	19037.5	348238.3	253464.8	47426.3	177134.2	299732.3	19160.4	348238.3	1145156	17.1
167	{USA},{JPN,EU,CHN,FSU}, {ROW}	253722.2	47376.6	176572.6	299713.5	19038.2	347037.4	253722.2	47405.3	176644.5	299498.8	19152.3	347037.4	1143461	11.5
173	{USA,JPN,EU,FSU},{CHN},{ROW}	253282	47396.9	176655.7	300001.6	19094.0	346569.3	253283.1	47394.9	176602.3	300001.6	19148.3	346569.3	1142999	9.9
195	{USA},{JPN,EU,FSU},{CHN},{ROW}	253219.5	47369.1	176534.5	299267.3	19120.0	345276.0	253219.5	47372.5	176511.4	299267.3	19139.7	345276.0	1140787	2.6
203	{USA},{JPN},{EU},{CHN},{FSU}, {ROW}	253104.6	47364.1	176477.5	299040.1	19136.5	344878.6	253104.6	47364.1	176477.5	299040.1	19136.5	344878.6	1140001	0.0

* Rank: rank of coalition structure in the list of all coalition structures sorted in descending order of global welfare (column "World"); valuations are billion US dollars expressed in 2000 levels, rounded to the first digit; World: sum of valuations of all six regions (i.e. global welfare); CGX: global welfare expressed in terms of closing the gap index: $100\cdot\left(\sum_{i=1}^{n}(v_i(c)-v_i(c^N))\right)/\left(\sum_{i=1}^{n}(v_i(c^F)-v_i(c^N))\right)$ where welfare is discounted lifetime consumption integrated over 2000-2300 (see section 3.1), global welfare with full cooperation is denoted by $\sum_{i=1}^{n}v_i(c^F)$ (c^F =coalition structure No. 1), global welfare with no cooperation is denoted by $\sum_{i=1}^{n}v_i(c^N)$ (c^N =coalition structure No. 203) and global welfare in some coalition structure c is denoted by $\sum_{i=1}^{n}v_i(c)$; abbreviation of regions as explained in the text in section 3.1; bold numbers indicate highest valuation of a region among the set of valuations $V(C)$ and $V^T(C)$, respectively.

Table 2: Equilibrium Coalition Structures for No Transfers and Transfers*

No Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,FSU},{JPN},{CHN,ROW}	1	1	1	5	9	1	1	80.7	yes/yes	32
{USA,JPN,EU},{CHN,ROW},{FSU}	3	3	3	6	1	2	2	80.3	yes/yes	52
{USA,EU},{JPN},{CHN,ROW},{FSU}	5	2	4	8	2	3	3	78.2	yes/yes	515
{USA,JPN,FSU},{EU},{CHN,ROW}	2	5	2	9	5	4	4	76.2	yes/yes	1
{USA},{JPN},{EU,FSU},{CHN,ROW}	4	4	5	10	4	9	5	73.7	no/no	16
{USA},{JPN,EU},{CHN,ROW},{FSU}	6	6	6	11	3	10	6	73.4	no/no	4
{USA,ROW},{JPN},{EU,FSU},{CHN}	8	7	7	1	10	5	7	72.2	no/yes	8
{USA,ROW},{JPN,EU},{CHN},{FSU}	9	10	8	2	6	6	8	71.9	no/yes	10
{USA,ROW},{JPN,FSU},{EU},{CHN}	10	8	9	3	8	7	9	71.3	no/yes	2
{USA,ROW},{JPN},{EU},{CHN},{FSU}	11	9	10	4	7	8	10	70.8	no/yes	78
{USA},{JPN},{EU,ROW},{CHN},{FSU}	7	11	11	7	11	11	11	63.8	no/no	2
								∅ = 77.3		

Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,CHN,ROW},{JPN},{FSU}	2	1	1	1	1	1	1	94.6	yes/yes	706
{USA},{JPN},{EU,FSU},{CHN,ROW}	1	2	2	2	2	2	2	73.7	no/yes	14
								∅ = 94.2		

* Ranking: ranking of equilibrium coalition structures in terms of valuations "World" in descending order; CGX: closing the gap index as explained in Table 1, ∅ =average welfare over all possible index sequences; PO: first entry = Pareto-optimal coalition structure in the set of all coalition structures, second entry = Pareto-optimal coalition structure in the set of equilibria; FR: frequence of appearance of coalition structure as an equilibrium out of the total number of index sequences that is 720.

Table 3: First-Mover Advantage to Enforce Best and to Avoid Worst Equilibrium*

No Transfers						
	USA	JPN	EU	CHN	FSU	ROW
Best Equilibrium	**93.8**	43.8	18.8	**100**	**73.1**	18.8
Worst Equilibrium	**15.4**	100	**0**	50	**0**	**0**
Transfers						
	USA	JPN	EU	CHN	FSU	ROW
Best Equilibrium	**100**	**50.4**	**50.1**	49.3	**50.1**	**51**
Worst Equilibrium	**49**	**28.6**	**42.9**	85.7	**42.9**	**0**

* Numbers are percentages of region i having an index number equal or smaller than 3 with respect to the the best and worst equilibrium coalition structure from player i's perspective in Table 2. Bold entries: %>50 for Best Equilibrium and %<50 for Worst Equilibrium indicate first-mover advantage.